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REPORT OF INVESTIGATIONS—NO. 42

SOME GEOLOGICAL RELATIONS BETWEEN
THE CONSTITUTION OF SOIL MATERIALS
AND HIGHWAY CONSTRUCTION

BY

GEORGE E. EKBLAW AND RALPH E. GRIM



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URBANA, ILLINOIS

1936

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SOME GEOLOGICAL RELATIONS BETWEEN THE CONSTITUTION OF SOIL MATERIALS AND HIGHWAY CONSTRUCTION¹

GEORGE E. EKBLAW² AND RALPH E. GRIM³

GEOLOGY AND ENGINEERING

GEOLGY is an important factor in practically every engineering project that deals with earth materials. In some fields of engineering the geological factor is so evident that it is universally recognized; in others its relations to the engineering problems may be so obscure that it is overlooked or ignored. However, the part that geology plays in all fields of engineering is becoming ever better appreciated, as is demonstrated by the increasing attention and care that is being paid to adequate exploration and testing of geological materials and structures with reference to proposed dams and reservoirs, canals and locks, sewer trenches, tunnels, foundations for buildings and bridges, underpasses, excavations and fills, etc.

Although there has been highway engineering almost ever since man found it desirable to travel from place to place, the modern profession had its inception hardly more than a quarter of a century past. In that brief span of time it has achieved distinction favorably comparable to that attained by other older fields of engineering. When paved highways were first constructed, they were designed by engineers who were experienced in constructing paved city streets, gravel or stone pikes, railways, and similar developments. Since then the technique of highway construction in all its phases has progressed to a high degree, and searching investigations into many of its problems have been undertaken and aggressively pursued.

In the demand for paved highways that increased when the benefits of the first ones laid down were appreciated, one fundamental factor in their construction — the geological situation — was almost universally ignored as unimportant, generally from lack of knowledge of its possible consequences. However, these consequences have eventually made themselves evident, and

¹ Presented at the Twenty-eighth Annual Meeting of the Mississippi Valley Conference of State Highway Departments, Stevens Hotel, Chicago, Illinois, February 7, 1936, and at the Twenty-third Annual Conference on Highway Engineering at the University of Illinois, Urbana, February 28, 1936.

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as a result a policy of intelligent caution and investigation concerning geological matters is being rapidly adopted. The highway engineers in almost every state, as well as in the Federal bureau and in many county and similar organizations, are devoting more and more attention to the geology of the materials underlying and bounding the highway and of those of which the highway itself is built.

ENGINEERING GEOLOGY IN ILLINOIS

Not many years after the program of improved highway construction in Illinois was begun, there appeared certain difficulties which the engineers of the State Division of Highways recognized as probably due to geologic conditions. These problems were referred to the State Geological Survey for counsel and to them Dr. M. M. Leighton, Chief, gave his personal attention for several years. Through these services, as well as similar services provided for problems concerning dams and reservoirs and other engineering projects presented to the Survey, the field of engineering geology in the State was established. It grew rapidly so that in 1927 the Division of Engineering Geology of the State Geological Survey was organized, with Dr. Ekblaw in charge.

At first, the problems presented by the highway engineers concerned only landslides and mudflows, with consequent dislocation of alignment and fractured or wavy pavements, and estimates of earth and rock to be excavated in highway construction, but in the nearly nine years that Dr. Ekblaw has continued the cooperation with them, the highway engineers have presented scores of situations, no two of which have ever been identical although they can be grouped into a relatively few classes of problems. Moreover, as an undoubted result of the engineers' better acquaintance with geology and consequent better appreciation of its application in highway construction, the field included by the problems they have presented has steadily broadened. Landslides of all types and sizes, seepage and drainage, peat bogs, location of fills, materials for fills, character of aggregate materials, selection of proposed highway routes, heaving and cracking of pavements, bridge foundations, and grade separations — either underpass or overhead — include most of the specific problems. Also, in 1929 and 1930, at the request of the State Division of Highways, the State Geological Survey carried on over most of the State a detailed reconnaissance of limestone and sand and gravel deposits suitable for local sources of materials for secondary roads. Within the last two years the highway engineers have asked for particular information as to deposits of plastic clay suitable for use in stabilized gravel roads.

PRESENT TRENDS

An account of the geology concerned with some of these problems, its significance, and the measures consequently adopted would be interesting but would probably only duplicate experiences of every highway engineer. Therefore, the present discussion is restricted to some considerations concerning soil materials that have probably never occurred to engineers as having any special bearing on highway construction but which we hope to show are actually of fundamental importance, especially in view of the present emphasis on better subgrades, better subgrade drainage, and stabilized gravel roads. The same considerations also more or less directly play a part in many of the other geological highway construction problems.

The two most recent problems on which the Illinois State highway engineers have sought our geologic advice have emphasized these very considerations. The problems have concerned failure of pavements at localities and in situations where it would hardly be expected. One case occurred in Lake County, where in situations that appear to have at least reasonably good drainage it is found that at times of heavy rain, water collects between the pavement and the subgrade, softens the surface of the subgrade, and thereby destroys its supporting power; the pavement vibrates under impact of traffic and pumps muddy water out through joints, cracks, and along the sides of the slab; and eventually so much of the subgrade is thus removed along transverse joints that the pavement settles, cracks, and is ruined. The other case occurred in Greene County, where in similar situations of apparently reasonably good drainage a "black-top" pavement has repeatedly failed. Again examinations revealed that during rainy periods water accumulates between the bearing course and subgrade, the pavement vibrates under traffic and pumps out muddy water through cracks, thus removing the supporting base, and eventually the pavement fails. An added factor in this case is the fact that because the pavement is not rigid, traffic traveling in relatively narrow lanes tends to press the pavement in these lanes down into the subgrade when it is softened by the water, and thus creates ruts in the subgrade in which more water accumulates, aggravates the situation, and hastens the disruption of the surface. It is obvious that these undesirable conditions result solely because the soil material on the subgrade and in the shoulders is relatively so impervious that the water cannot escape either downward or laterally but accumulates between the pavement and the subgrade; it is also obvious that the remedy consists of altering or amending the construction design to provide means either of preventing excess water, especially that drained off the pavement surfaces themselves, from getting under the slab or of removing it as rapidly as it accumulates. However, these conclusions do not answer the question raised by the engineers as to why such conditions occur at some places and not universally in the State. The studies of clay

minerals as carried on by Dr. Grim during the past four years and as applied to soil materials provide some interesting data pertinent to the question.

SURFICIAL MATERIAL

In Illinois, as in the other states of the Mississippi Valley, most of the subgrade on which highways are constructed is unconsolidated material, and in the states in the upper Mississippi Valley a part of the unconsolidated

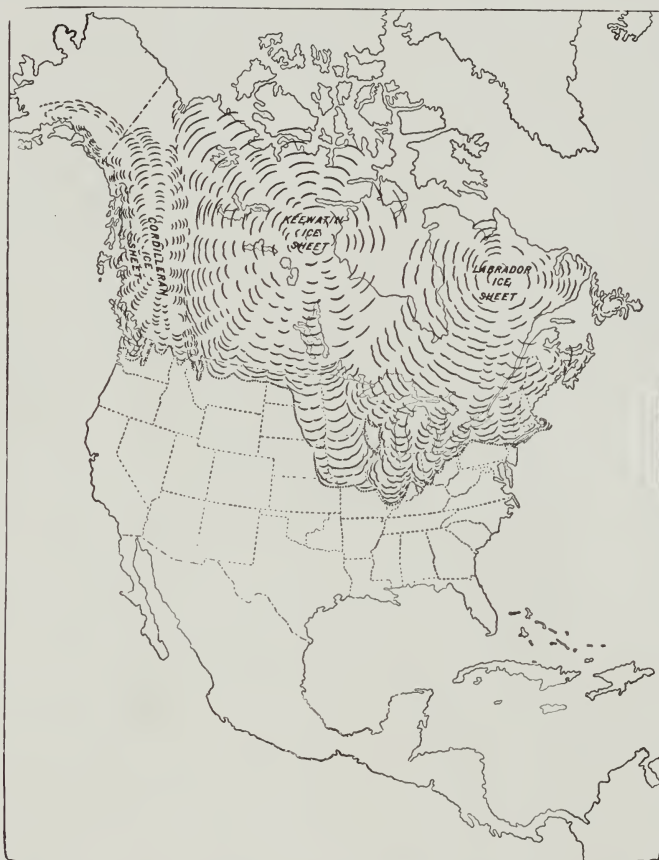


Fig. 1.—MAP OF NORTH AMERICA SHOWING THE CENTERS OF ICE ACCUMULATION AND THE AREA OF GLACIATION

material is glacial drift, that is, material that was picked up by the continental glaciers which spread from Canada over northern United States, was carried by them to localities far from their source, and was dropped when the glaciers melted away (Fig. 1). Much of the surficial material is loess, a deposit of silt derived from various sources and carried and laid down by the wind, and the rest is alluvium deposited either by glacial or present streams.

Four distinct glaciers successively invaded northern United States and are named, in order of age, Nebraskan, Kansan, Illinoian, and Wisconsin (Table 1). Between each two glacial stages there was an interval of time

TABLE 1.—THE GLACIAL STAGES OF NORTH AMERICA

Glacial invasions	Interglacial epochs
Wisconsin (fourth).....	Sangamon (third).....
Illinoian (third).....	Yarmouth (second).....
Kansan (second).....	Aftonian (first).....
Nebraskan (first).....	

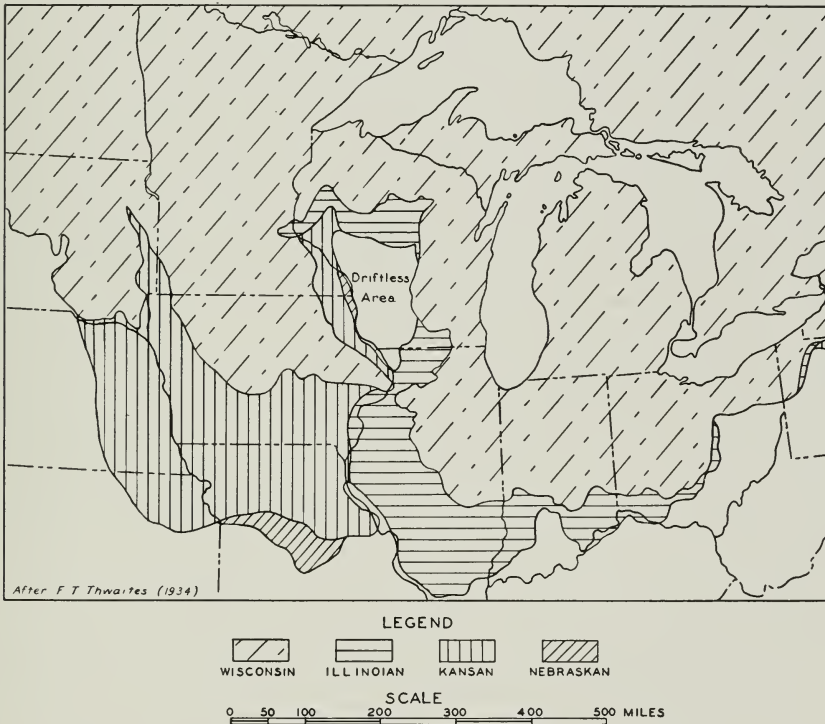


Fig. 2.—SURFICIAL DISTRIBUTION OF GLACIAL DRIFT-SHEETS IN THE UPPER MISSISSIPPI VALLEY

during which the climate was much the same as at present, so that on the preceding glacial drifts operated the same processes that are now operating, and one of these is the formation of soils. Consequently at some places we

find two or more deposits of glacial drift, each separated by a soil horizon. The Nebraskan and Kansan drifts are found in Nebraska, Kansas, southern Iowa, and Missouri as far south as Missouri River; the Illinoian drift occurs in southern and western Illinois, southeastern Iowa, southern Indiana, and southern Ohio; the Wisconsin drift covers northern Ohio, northern Indiana, northeastern Illinois, northern Iowa, and the other northern states (Fig. 2).

SOIL PROFILES

Geologists recognize that in the formations of soils there are four major chemical reactions which, in the order of their relative rate of progress, are respectively (1) formation of humus organic material, (2) oxidation, (3) leaching or solution of lime and magnesium carbonates, etc., and (4) decomposition of silicate minerals with consequent concentration of colloidal material.

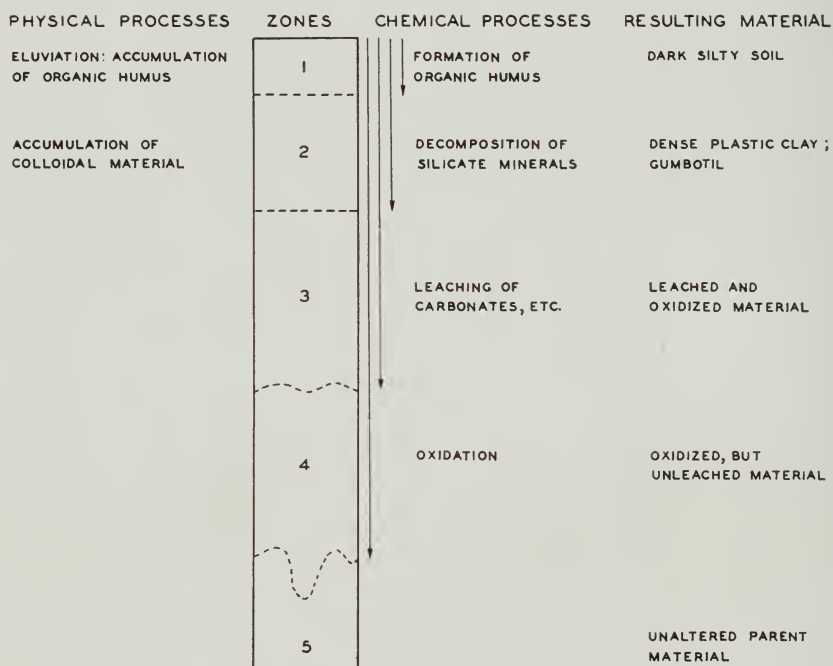


Fig. 3.—GENERALIZED DIAGRAM OF A MATURELY DEVELOPED SOIL PROFILE AND THE PROCESSES INVOLVED IN ITS DEVELOPMENT (After Leighton and MacClintock)

A typical well-developed soil profile on glacial material consists of four major horizons (Fig. 3) which, from top to bottom, are (1) the humus horizon, a black or gray silty zone generally not more than several inches thick, (2) a zone of dense oxidized leached clay, typically gray but locally reddish, hard when dry and generally plastic when wet, and practically impervious to all

drainage, (3) an oxidized, leached zone, and (4) an oxidized but calcareous zone, beneath which occurs the unaltered parent material (5). The thickness of these zones depends on the length of time the soil-forming processes have operated. All of them are well developed in the soil profiles formed on all the glacial drifts except the last one (Wisconsin). Because zone 2, when typically developed from glacial till over broad flat areas, is extremely plastic and gumbo-like, it has been termed gumbotil. It is a reliable source of plastic clay in almost all of the territory covered by the three older glacial drifts. Zone 2, as developed on deposits of fine loess, is also a possible source of plastic clay but is not so satisfactory as the gumbotil. The density and general imperviousness of this zone are the factors that contribute so greatly to the problem of satisfactorily draining subgrades in so many places in the Mississippi Valley.

With these general relationships of glacial drifts and soil-profile zones in mind, we shall proceed to a consideration of the constitution of clays and soils.

RELATIONS BETWEEN CONSTITUTIONS AND PROPERTIES OF CLAYS AND SOILS

It is obvious that the character and properties of the materials on which the highways are directly laid will exert a tremendous influence on their durability and permanence. Every engineer knows that not all soils possess the same properties and that different soils yield different results when highways are built over them or when they are used in fills. Further, it is obvious that the most satisfactory material for fills cannot be selected from that available in a given area and the most satisfactory subgrade drainage cannot be designed until it is known why different soils possess different physical properties. This knowledge is necessary before an examination and consequent determination that certain specific materials will have certain properties and other material will have other specific properties can be intelligently made.

Soils, clays, tills, loess, and shale are all argillaceous materials—that is, they contain clayey material and possess properties, such as plasticity when wet, which are associated with the term clay. The physical properties of argillaceous materials are dependent upon their constitution. The important factors of constitution influencing physical properties are texture, chemical composition, mineral composition, and base-exchange characteristics. The literature contains the results of much research on the influence of the first two factors. It is known, for example, that in general the finer the grain size of such material, the greater the plasticity, water adsorptive ability, shrinkage, etc., and that electrolytes exert a great influence on the degree to which clays can be placed in suspension in water. More recent research has emphasized the importance of the mineral composition and base-exchange characteristics as factors determining the properties of argillaceous materials.

It has shown that two clays may have the same grade size distribution and yet possess different physical properties if their mineral compositions are different. Likewise, two clays may yield the same ultimate chemical composition but possess different physical properties if their mineral compositions and base-exchange characteristics are different. Research into the mineral composition and base-exchange properties of argillaceous materials and the influence of these factors of constitution on physical properties has been Dr. Grim's major interest in recent years.

DETERMINATION OF CONSTITUTION OF CLAYS AND SOILS

Complete research into the mineral composition of these materials is of relatively recent date for the reason that satisfactory research tools and methods for studying the finest constituents have been only recently developed. It is comparatively easy to identify the mineral constituents in the coarser grade sizes, but special technique is necessary to identify those in the finest grade sizes, particularly those of colloidal size, that is, those which have to be measured in fractions of a micron. In the laboratory of the Illinois State Geological Survey a research procedure has been devised whereby complete thoroughgoing data on the mineralogy of clays can be obtained by special microscopic technique using magnifications up to 1500 diameters, by improved X-ray technique, and by chemical analysis following separation of the material into mineral concentrates by means of a supercentrifuge. The clays are literally taken apart into their component mineral constituents. It is these constituents in the finest fractions which are most important in influencing physical properties.

This work has shown (1) that the concept that all clays contain a mysterious universal clay substance, sometimes called clayite, to which they owe their properties, is fallacious; (2) that the concept that all clay materials are composed essentially of the mineral kaolinite is erroneous; (3) that an alternative concept that these materials are simply heterogeneous assemblages of almost any species of minerals existing in very small particles and that therefore their properties are entirely dependent upon the size-grade distribution of the component particles is also erroneous; and (4) that they contain little or no amorphous material.

On the contrary, this work has shown that clays actually are composed of crystalline constituents throughout—even the colloidal fraction is composed of crystalline particles, the colloidal properties depending on smallness of particle size and also on the shape of the individual particles. It has also substantiated the concept, which has become increasingly prevalent in recent years, that argillaceous materials are composed essentially of one or more of a comparatively small group of minerals known as the clay minerals (Table 2).

TABLE 2.—CLAY MINERALS

Name	Chemical composition	Remarks
Kaolinite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Anauxite and kaolinite form an isomorphous series
Anauxite	$\text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	
Halloysite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot x\text{H}_2\text{O}$	
Beidellite	$\text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot x\text{H}_2\text{O}$	Beidellite and nontronite form an isomorphous series
Nontronite	$\text{Fe}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot x\text{H}_2\text{O}$	
Montmorillonite	$\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$	
Sericite-like mineral	$2\text{K}_2\text{O} \cdot 3\text{MO} \cdot 8\text{R}_2\text{O}_3 \cdot 24\text{SiO}_2 \cdot 12\text{H}_2\text{O}$	Montmorillonite, beidellite, and nontronite probably contain essential alkalis or alkaline earths.

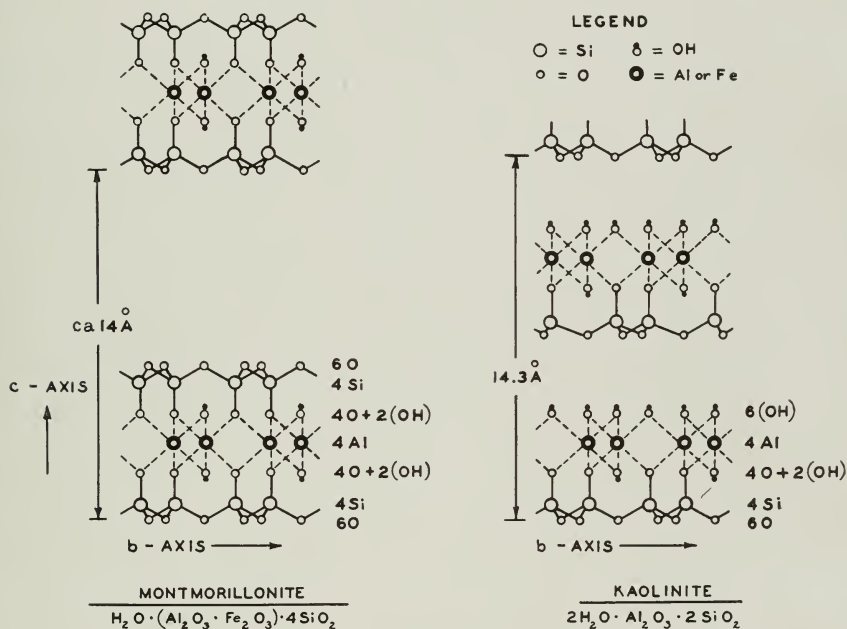


Fig. 4.—SCHEMATIC REPRESENTATION OF LATTICE STRUCTURE OF THE CLAY MINERALS MONTMORILLONITE AND KAOLINITE (after Endell, Hofmann, and Wilm) showing the layered arrangement that accounts for their flake-like crystals. Note the great and variable interval between the successive layers in montmorillonite, as compared with the limited interval in kaolinite, which accounts for its greater adsorptive ability and other properties.

They are hydrous aluminum silicates and some of them also contain alkalis or alkaline earths. In most of them the aluminum may be isomorphously replaced by ferric iron. At the present stage of the researches, it is not possible to write exact formulae for all of them; the formulae of beidellite, nontronite, and the unnamed sericite-like mineral particularly are to be regarded as

tentative. The sericite-like mineral is so named because it resembles the sericite form of white mica. It is possible that future research will show that there are a few other clay minerals. All the clay minerals have a general micaceous crystalline habit, as a consequence of which their individual particles are flat and flake-shaped (Fig. 4). It is important to note that the flake-shaped characteristic is not developed to the same degree in all clay minerals.

COMPOSITION OF SOME COMMON "SOIL MATERIALS"

The essential features of the mineral composition of the several argillaceous materials commonly encountered in highway construction are as follows:

Gumbotil is composed essentially of beidellite in particles .00006 mm. in diameter or in slightly larger particles, .001-.0001 mm. in diameter, which are easily reduced by slight working of the material to the finer grade size. In addition to beidellite, silty gumbotil contains the sericite-like mineral and also quartz varying in amounts according to the degree of siltiness. Coarser grains of quartz and possibly large grains of other minerals are present if the gumbotil is sandy.

The finest grade sizes, that is clay-size grades, of *till* are composed of a mixture of beidellite and the sericite-like mineral. If the till is calcareous, calcite is present in particles which may attain a minimum size of .0001 mm. The coarser fractions of till are mixtures of quartz and fragments of a variety of different minerals and rocks. Different tills vary from each other in the relative abundance of these constitutions, but the relative abundance of beidellite and the sericite-like mineral are of prime importance in influencing physical properties.

Loess is composed primarily of quartz and mica with a smaller quantity of a variety of other minerals, such as feldspar, pyroxene, and amphibole, all existing in particles ranging in size from about .06 to .001 mm. A small amount of finer material, which is a mixture of beidellite and the sericite-like mineral, is present. Calcite is present if the material is calcareous.

The finest grade sizes of *soil developed on loess* in Illinois are a mixture of beidellite, the sericite-like mineral, organic material, limonite (hydrated ferric oxide), and quartz. The coarser fractions have compositions similar to those of the coarser fraction of the loess from which the soil was derived. These constituents are not present in uniform amounts in all soils nor are they uniformly distributed vertically from the top of the soil downward, but are to a large degree dependent on the maturity of the soil and the drainage conditions under which it has developed. Thus, organic material tends to occur mainly in the surface horizon (Fig. 3, zone 1). Beidellite is a secondary product derived from the alteration of many of the primary constituents. It forms primarily in the upper horizon and as the soil profile

develops it is carried downward and redeposited a short distance beneath the surface. As a result, zone 2 of the soil profile is formed as an impervious horizon, whose thickness and depth vary with the age of the soil, and at the same time the top horizon consequently becomes increasingly silty. When the soil profile has reached a fairly advanced stage of weathering, the beidellite is decomposed into its constituent oxides and rounded limonitic aluminous pellets tend to develop at or near the base of zone 2. The process of leaching, by which downward seeping groundwater removes from the upper horizon not only the calcite but also any alkalis that may be present, causes the upper horizons of the soil profile to become acid.

RELATION BETWEEN MINERAL CONSTITUENTS AND PROPERTIES OF SOILS

The next step of our research has been to determine the influence that specific mineral constituents exert on the physical properties of the materials containing them. It has been found, for example, that beidellite and montmorillonite differ from kaolinite and the sericite-like mineral in possessing far higher adsorptive ability for water; in the ability to break down easily to extremely small particles, e. g., beidellite commonly occurs in particles less than .00006 mm. or can easily be reduced to this size whereas the sericite-like mineral and kaolinite rarely are in particles smaller than .0001 mm.; and in their ability to possess exchangeable bases. It follows from these and other considerations that increasing amounts of beidellite in a soil will increase its plasticity, its stickiness, its impervious character, and the swelling and shrinkage on the addition or removal of moisture. Stated another way, two soils, one of which is largely composed of beidellite and the other of the sericite-like mineral, may have about the same size grade distribution in the natural state and about the same ultimate chemical analysis, but when these soils are utilized, the one containing the most beidellite will tend to be most impervious, stickiest, most plastic, and most subject to volume variation.

The addition of electrolytes has been known for some time to cause changes in the physical properties of clays. In the last few years the relation of this phenomenon to base-exchange has been recognized and its importance has been realized. Clays possess the ability to carry bases which, under certain conditions, can be exchanged for other bases. Thus, if a clay containing exchangeable calcium is treated with a strong solution of a sodium salt, the sodium will go into the clay replacing the calcium which will come out in the solution. Opinions differ as to whether the exchangeable bases are held on the surface of the colloidal particles or within their lattice structure. Likewise, opinions differ as to whether it is a stoichiometrical chemical reaction or simply adsorption.

The seat of the exchange capacity is in the clay mineral content, and different clay minerals possess different exchange capacities. Thus, the exchange

capacity for montmorillonite is very high, for beidellite it is moderately high, and for kaolinite and the sericite-like mineral it is low. Obviously soils composed of beidellite will have higher exchange capacity than those composed of the sericite-like mineral. Therefore, whatever influence base-exchange phenomena exert on physical properties will be reflected to a higher degree by those composed of beidellite than those composed of the sericite-like mineral.

Certain properties of soils vary with the identity of the exchangeable base they contain. For example, the plasticity of a given clay or soil differs according to whether sodium or calcium is the exchangeable base. The shrinkage can be changed by substituting calcium for sodium. A soil saturated with sodium is far more impervious to water than an acid soil or one in which calcium is the exchangeable base.

The reason for this influence may be conceived in part by considering the flake-shaped clay mineral particles to be encased in a hull of basic ions which in turn is enclosed by a hydration sphere. Probably because different ions have different dissociation abilities, the hydration sphere varies with the identity of the exchangeable base and the physical properties show a correlative variation.

In the present state of information it is impossible to give much specific data and many detailed conclusions on this subject. The Illinois State Geological Survey has under way extensive researches to determine the constitution, particularly the mineral constitution, and base-exchange characteristics of the argillaceous materials occurring within the State. Our object is further to determine exactly how these factors influence the properties of the material as a whole, which, in turn, determine its utilizations, and thereby to extend and to improve their utilization in the field of ceramics and in other fields in which such materials are used. Our researches have progressed so far that a comparatively rapid petrographic microscopic analysis of the mineral composition of these materials commonly enables a prediction of their physical properties. However, this procedure is not intended as a substitute for actual testing, but its value lies primarily (1) in selecting from material available that which is most satisfactory for a given purpose, and (2) in the search for the seat of trouble in material which has already been used

